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6. AUTHORS
J.J. Garcia-Luna-Aceves, Ra jive Bagrodia, Anthony Ephremides, Mario Gerla, Andrea Goldsmith, Muriel Medard, Katia Obraczka, Hamid Sadjadpour, Nitin Vaidya, Pravin Varaiya

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of California - Santa Cruz
1156 High St

Santa Cruz, CA 95064 -1077

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14. ABSTRACT
The DAWN (Dynamic Ad-hoc Wireless Networks) project is developing a general theory of complex and dynamic wireless communication networks. To accomplish this, DAWN adopts a very different approach than those followed in the past and summarized above. DAWN considers a cross-disciplinary approach incorporating the effects of the physical layer explicitly into the modeling, analysis, and control of wireless communication networks. The members of DAWN investigated difference aspects of wireless mobile ad hoc networks (MANET).

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UU	UU	UU	UU		Jose Garcia-Luna
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					831-459-4153

Report Title

Final Report: DAWN: Dynamic Ad-hoc Wireless Network

ABSTRACT

The DAWN (Dynamic Ad-hoc Wireless Networks) project is developing a general theory of complex and dynamic wireless communication networks. To accomplish this, DAWN adopts a very different approach than those
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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
03/15/2007 27.00	Ning Li, Jennifer C. Hou. A Scalable, Power-Efficient Broadcast Algorithm for Wireless Networks, , ( ): . doi:
03/15/2007 28.00	Ning Li, Jennifer C. Hou. Localized Topology Control Algorithms for Heterogeneous Wireless Networks, IEEE Transactions on Networking, ( ): . doi:

TOTAL: **2**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
05/01/2016	47.00	Marzieh Veyseh, J.J. Garcia-Luna-Aceves, Hamid R. Sadjadpour. Multi-User Diversity in Single-Radio OFDMA AdHoc Networks Based on Gibbs Sampling, IEEE Milcom . 03-NOV-10, . : ,

TOTAL: **1**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

03/15/2007 29.00 Ting-Yu Lin, Jennifer C. Hou. Interplay of Spatial Reuse and SINR-Determined Data Rates in CSMA/CA-Based, Multi-Hop, Multi-Rate Wireless Networks,
( )

05/01/2016 44.00 Hui Xu, , Xianren Wu, , Hamid R. Sadjadpour, , J.J. Garcia-Luna-Aceves, . A Unified Analysis of Routing Protocols inMANETs,
IEEE Transactions on Communications (03 2010)

05/01/2016 46.00 Hui Xu, , J.J. Garcia-Luna-Acevesl,, Hamid R. Sadjadpour. Enabling Multi-Packet Transmission and Reception: An Adaptive MAC Protocol for MANETs,
Lecture Notes of the Institute for Computer Science, Social Informatiocs and Telecommunication Engineering Springer (06 2010)

05/01/2016 45.00 Zheng Wang, , Hamid R. Sadjadpour, , J. J. Garcia-Luna-Aceves,, Shirish S. Karande,. Fundamental Limits of Information Dissemination inWireless Ad Hoc Networks—Part I: Single-Packet Reception,
IEEE Transaction on wireless communications (11 2009)

11/29/2007 33.00 Renato M. de Moraes, Hamid R. Sadjadpour, J.J. Garcia Luna Aceves. On the Link Ergodic Capacity of MIMO MANETs Using Cooperation,
( )

11/29/2007 35.00 R.M. de Moraes, H.R. Sadjadpour, J.J. Garcia Luna Aceves. CDMA Implementation for Many to Many Cooperation in Mobile Ad Hoc Networks,
( )

11/29/2007 34.00 R.M. de Moraes, Hamid R. Sadjadpour, J.J. Garcia Luna Aceves. Many to Many Communication: A New Approach for Collaboration in MANETs,
( )

12/03/2007 36.00 J.J. Garcia-Luna-Aceves, Hamid R. Sadjadpour, Zheng Wang. Challenges: Towards Truly Scalable Ad Hoc Networks,
( )

12/03/2007 37.00 Zheng Wang, Hamid R. Sadjadpour, J.J. Aceves. Improving Scalability of Wireless Ad Hoc Networks Using MPR,
( )

12/03/2007 38.00 J.J. Aceves, H.R. Sadjadpour, Z. Wang. Extending the Capacity of Ad Hoc Networks Beyond Network Coding,
( )

12/03/2007 39.00 Xianren Wu, Hamid R. Sadjadpour, J.J. Aceves. Link Dynamics in MANETs with Restricted Node Mobility: Modeling and Applications,
( )

12/03/2007 40.00 Xianren Wu, Hamid R. Sadjadpour, J.J. Aceves. Routing Overhead as a Function of Node Mobility: Modeling Framework and Implications on Proactive Routing,
( )

12/03/2007 41.00 Xianren Wu, Hamid R. Sadjadpour, , J.J. Aceves. Analytical Modeling of Link and Path Dynamics and Their Implications on Packet Length in MANETs,
( )

12/03/2007 42.00 Xianren Wu, Hamid R. Sadjadpour, J.J. Aceves. From Link Dynamic to Path Lifetime and Packet length Optimization in MANETs,
( )

12/03/2007 43.00 Xianren Wu, Hamid R. Sadjadpour, J.J. Aceves. Link Lifetime as a Function of Node Mobility in MANETs with Restricted Mobility: Modeling and Applications,
( )

TOTAL: **15**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

None.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Zheng Wang	1.00	
Xianren Wu	1.00	
Marzieh Veizeh	0.50	
Hui Xu	1.00	
Stephen Dabibeem	0.50	
FTE Equivalent:	**4.00**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Shirish Karande	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Katia Obraczka	0.20	
Rajive Bagrodia	0.20	
Hamid R. Sadjadpour	0.20	
JJ Garcia-luna-aceves	0.20	
Anthony Ephremides	0.20	
Mario Gerla	0.20	
Andrea Goldsmith	0.20	
Muriel Medard	0.20	
Nitin Vaidya	0.20	
Pravin Varaiya	0.20	
FTE Equivalent:	**2.00**	
Total Number:	**10**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Xianren Wu
Zheng Wang
Marzieh Veizeh
Hui Xu

Total Number: 4

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The summary of scientific progress is given in the attachment.

Technology Transfer

None.

Contents

1 Introduction

The network-centric battlefield includes sensors, troop carriers, unmanned air vehicle (UAV), aircraft, smart weapons, soldiers, and command centers all interconnected in the battlefield. In network-centric battlefield, wireless link quality, connectivity and other features of the network change constantly while information is required to be disseminated among nodes. This project focuses on development of the theoretical foundations for designing reliable MANETS that meet the stringent military requirements.

To address these challenges, we have established the Dynamic Ad-hoc Wireless Networks (DAWN) project. This project developed a complete theory of complex and dynamic wireless communication networks. DAWN project started many new cross-disciplinary initiatives such as considering physical layer effects into the modelling, analysis and control of wireless networks. DAWN systematically redefined and reorganized existing models, protocols and controls, and developed new ones in a framework that guarantees realism and cross-layer consistency to enable the efficient design of such complex wireless systems as those required by the U.S. Army.

2 Scientific Achievements

This section highlights some of the scientific achievements during this project. These are few samples that represent the quality of the research work conducted during this program.

2.1 Executive Summary

DAWN PIs had received numerous awards in different venues as reported in our prior interim reports. We have also published many IEEE and ACM journal and conference papers. We have also developed key results that can be summarized below. Key results include: (a) The computation of optimal unicast capacity and the technique to achieve this capacity; (b) showing that network coding (NC) does not provide order throughput gains in wireless ad hoc networks subject to multicast communication; and (c) establishing a unifying framework for the capacity of wireless networks subject to any type of information dissemination modalities, and employing MPR or MPT. We have also developed the first modeling of topology evolution in wireless mobile ad hoc networks (MANETs), a unifying analytical framework for routing protocols in MANETs, more accurate performance models for 802.11 channel access, and novel results on the impact of network coding on the throughput and delay in wireless networks. We have also developed cross-layer multicasting design for wireless ad hoc networks, including modeling of topology evolution in wireless MANETs and unified analytical framework for routing protocols in MANET.

2.2 **Unified Approach in Information Dissemination**

In this section, we present the first unified modeling framework for the computation of the capacity-delay tradeoff of wireless ad hoc networks. The general solution for modeling information dissemination encompasses unicast routing, multicast routing, broadcasting, or different forms of anycasting. It is termed *(n,m,k)*-casting as a generalization of all forms of one-to-one, one-to-many, and many-to-many information dissemination in wireless ad hoc networks. In this context, *n, m,* and *k* denote the total number of nodes in the network, the number of destinations for each communication group, and the actual number of communication group members that actually receive information $(k \leq m)$, respectively. Based on this framework, the capacity-delay tradeoff for *(n,m,k)*-casting in wireless ad hoc networks was derived. The results are consistent with many research results that were developed by other researchers for specific values of *n, m,* and *k* while it provides also new results that can only be derived with this new approach.

There is much valuable insight to be gained from modeling the capacity of unicasting, multicasting, broadcasting and anycasting using the same framework. Our *(n, m, k)*-cast framework allows us to analyze the throughput capacity of wireless networks as a function of the number of receivers of a communication group, which can range from 1 up to the number of nodes in the network, as well as a function of the transmission range. Accordingly, the results obtained in all prior work can be derived from our model by selecting the appropriate values for transmission range, *(n)*, and *m*. In addition, our framework also provides new insight on the capacity of information dissemination

techniques that are becoming more prevalent with the availability of in-network storage, namely anycasting, and allows us to reason about the nature that route signaling should be rendered more scalable wireless networks.

The relationship between capacity, $C_{m,k}(n)$, and the transmission range $r(n)$ can be seen in Fig. 1. From this figure, we see that maximum capacity can be attained when the transmission range has its minimum value, i.e., $r(n) = \Omega\left(\sqrt{\frac{\log(n)}{n}}\right)$. We observe that the throughput capacity of dense wireless ad hoc networks is proportional with $\Theta\left(\frac{\sqrt{m}}{k}\right)$ and inversely proportional with the transmission range (n).

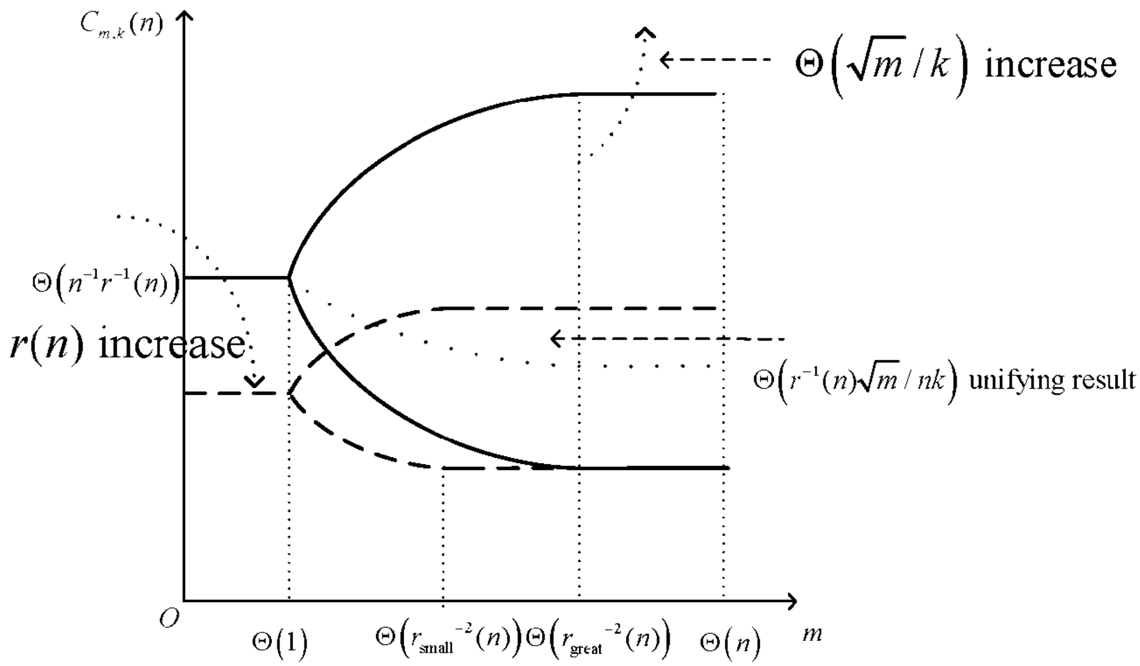

Fig. 1. $C_{m,k}(n)$ as a function of transmission range $r(n)$, real number of destinations k, and the number of destination group choices m.

Fig. 2 shows $C_{m,k}(n)$ as a function of m. As it was the case for $C_{m,m}(n)$ if m varies from 1 to $m_u = \Theta(1)$, the capacity of the network does not change and equals $\Theta\left(\frac{1}{\sqrt{n\log(n)}}\right)$. For values of larger than m_u, the (n, m, k)-cast order capacity can increase or decrease depending on the value of k. The smallest order capacity corresponds to the case when $k = m$, i.e., multicasting ($m < n$) or broadcasting ($m = n$), and the largest order capacity is attained for anycasting ($k = 1$). The shaded area in the figure shows the achievable capacity for manycasting ($1 < k < m$) for different values of m and k. We observe that, regardless of the value of k, the capacity of wireless ad hoc networks becomes constant when $m = \Omega(n/\log n)$ and an increase in the value of m does notchange the throughput capacity. This result can be understood

by the fact that, when the number of destinations reaches $\Theta(n/\log n)$, this set becomes the connected dominating set (CDS($r(n)$)) of the entire network as long as the transmission range $r(n)$ is chosen such that the network is a connected network. Equivalently, if a broadcast is made to the entire network, the capacity does not change because all the nodes in the network are either inside this set or within one hop from an element in this set.

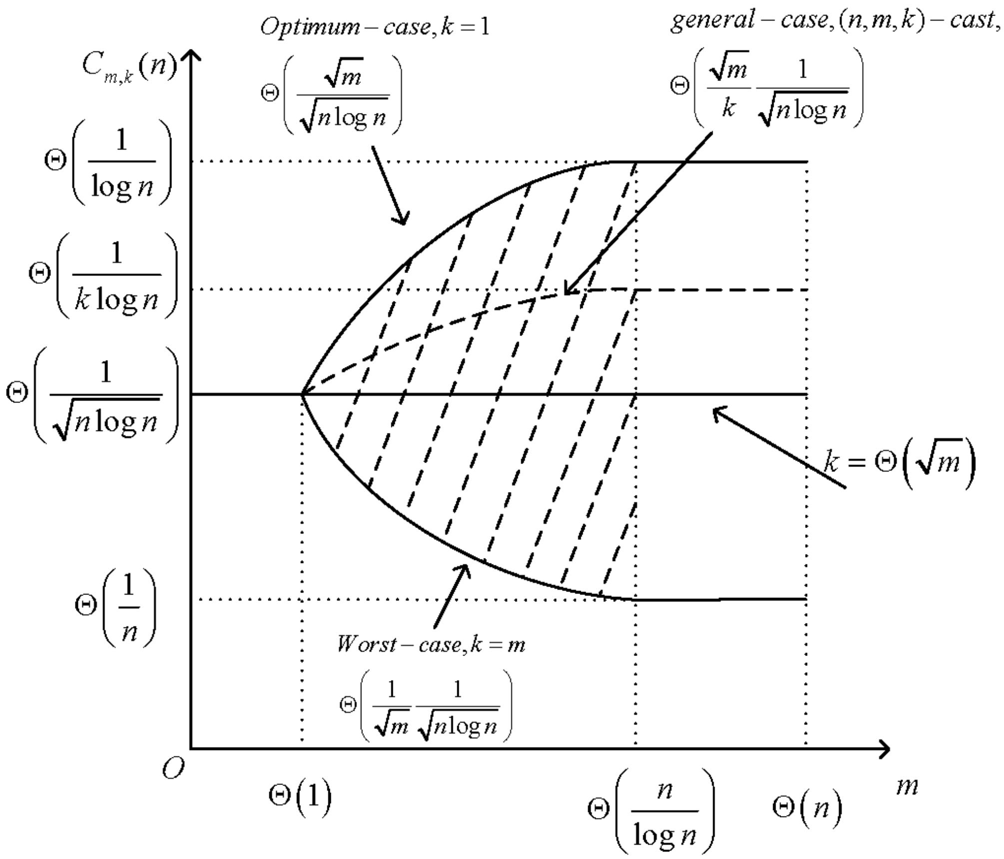

Fig. 2. Unifying view of throughput capacity.

2.3 **Unified Analysis in Routing Protocols in MANETs**

We developed a mathematical framework for the evaluation of the performance of proactive and reactive routing protocols in mobile ad hoc networks (MANETs). This unified framework provides a parametric view of protocol performance, which in turn provides a deeper insight into protocol operations and reveals the compounding and interacting effects of protocol logic and network parameters. The parametric model comes from a combinatorial model, where the routing logic is synthesized along with the characterization of MAC performance. Each wireless node is seen independently as a two-customer queue without priority, where the two types of customers are unicast and broadcast packets. The model captures the essential behavior and scalability limits in network size of both classes of routing protocols, and provides valuable guidance on the performance of reactive or proactive routing protocols under various network configurations and mobility conditions. The analytical results obtained with the proposed model are in close agreement with simulation results obtained from discrete event *Qualnet* simulations.

In the simulation results reported here, a total of 100 nodes initially randomly distributed over a square network of size 1000m × 1000m is considered. Every node moves at a speed V and transmits at uniform power of a coverage of radius R under certain traffic load. Three different transmission ranges $R \in \{150, 200, 250\}$ meters are covered, all within the coverage of WiFi devices. Four different speeds $V \in \{5, 10, 15, 20\}$ *m/s* are simulated, from lower mobility to higher mobility scenarios. Traffic, supplied from CBR source at rate 0.5p/s, is randomly generated with uniformly distributed sources and destinations. Different traffic flows $F \in \{1, 5, 10, 15, 20\}$ are simulated, covering low and

moderate flow configurations. In addition, simulation results are obtained for both reactive (AODV) protocol and proactive (OLSR) protocol using the default implementation in *Qualnet 3.9.5*. The MAC layer is chosen as the default implementation of 802.11 MAC in *Qualnet*. Overall, a total of 120 different {radius, mobility, flow, protocol} configurations are simulated. For each configuration, the simulation result is obtained from 10 random runs. Each simulation run is conducted at a randomly generated seed with a duration of 30 minutes.

Let's first explore the effectiveness and correctness of the proposed model in analyzing the general behaviors of routing protocols, in terms of protocol efficiency or packet delivery ratio (PDR), under various {mobility, traffic flow} configurations. Note that when evaluating proactive protocols, the proposed model has been adapted to incorporate the analysis of OLSR protocol, accounting for artifacts from Multi-Packet Receiver (MPR) technique.

From Figs. 3 to 6, we have such observations,

• When adapted to specific protocols, the proposed analytical model provides satisfactory approximation to simulated performance, as observed from similar behavior in Figs. 5 and 6 for OLSR protocol.

• Without incorporating specific techniques of AODV protocol (e.g. local repair), the propose model still captures the essential behaviors of reactive protocols with respect to mobility and traffic flows, while failing to provide good matches to simulated performance.

• The analytical results reveal that reactive protocols are more susceptible to traffic increase, while proactive protocols are robust to change in traffic. In general, as traffic

increases, a cross-point should be expected to signal the transition of preference to proactive protocols. The analytical findings corroborates similar simulation findings in literature.

• Design of MAC layer significantly affects protocol performance and network scalability. Illustrated in Figs. 3 and 4, GTDMA provide very low throughput (measured by protocol efficiency) and hit the bound of network scalability, while LTDMA scheme still enjoys good performance.

In summary, the parametric analytical framework provides key insights into the compounding and interacting effect of network parameters, deeper understanding on essential protocol behaviors and capability of approximating practical performance with incorporation of procotol-specifc techniques.

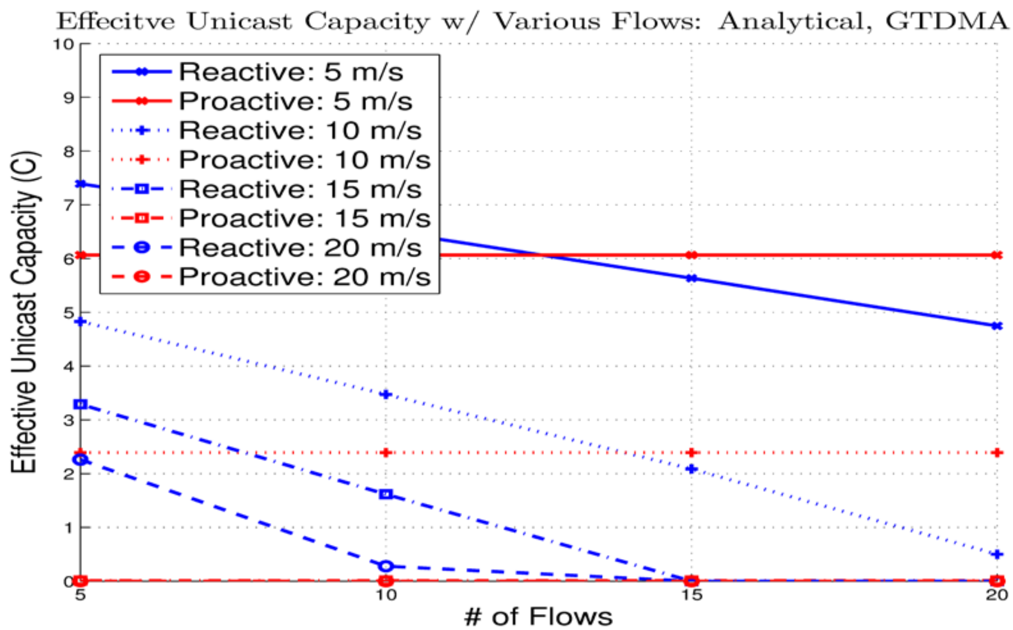

Fig. 3. Protocol Efficiency, Various Flows Analytical, GTDMA.

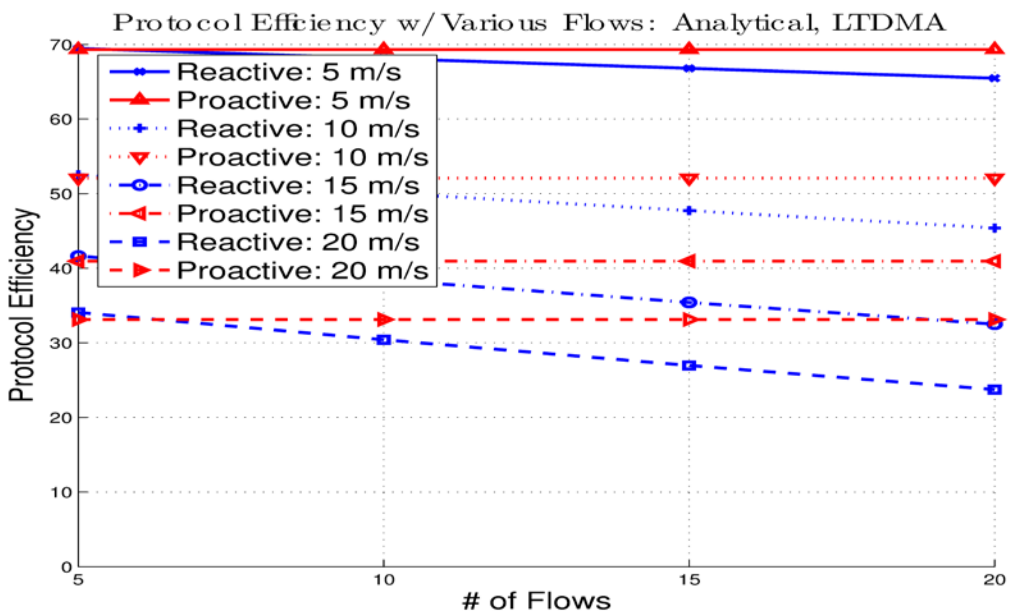

Fig. 4. Protocol Efficiency, Various Flows Analytical, LTDMA.

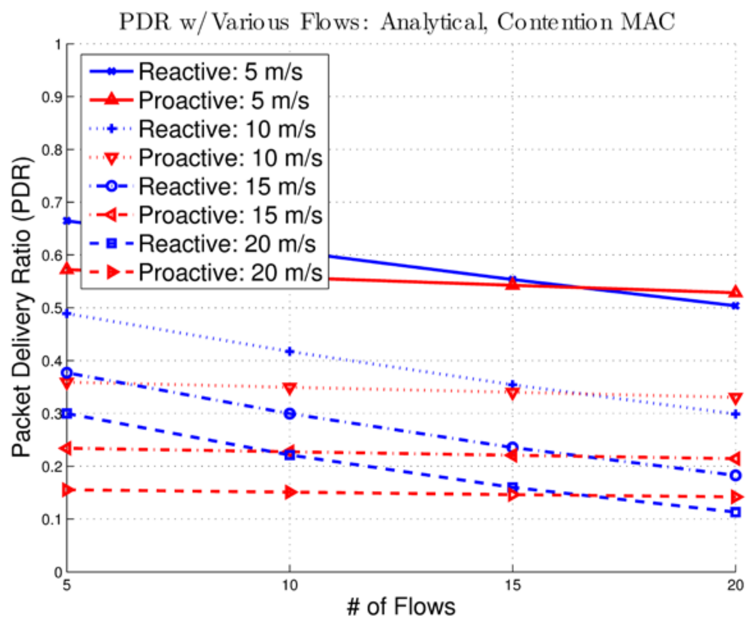

Fig. 5. Packet Delivery Ratio (PDR), Various Flows Analytical, Contention-based MAC.

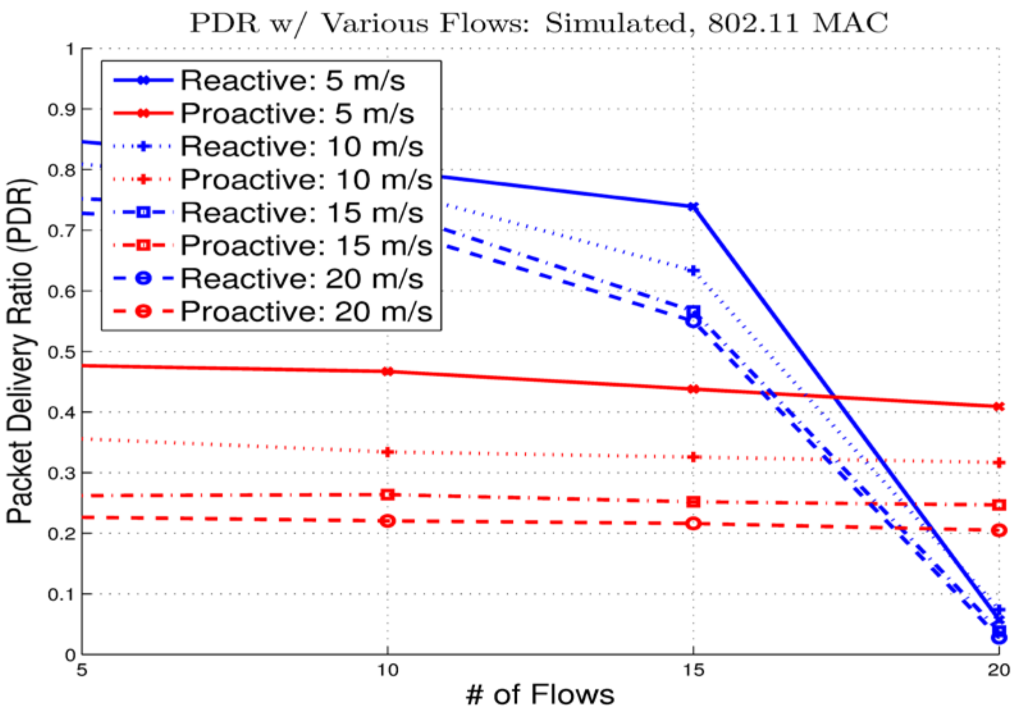

Fig. 6. Packet Delivery Ratio (PDR), Various Flows Simulated, 802.11 MAC.

It should be noted that in above figures only present the relationship between PDR and various number of flows. Therefore, now we look at one theoretical aspect of the model and are interested to know how the increment in transmission radius R affects protocol performance under various {mobility, transmission radius} configurations. Fig. 7 from the model immediately brings out the answer. The increase in R results in two conflicting effects: improvements in *logic efficiency*, resulting from the shorter source-destination distance; deterioratization in *operation efficiency* with more competing neighbor nodes. And proactive protocols should expect worse performance. The analytical explanations well agrees with the intuition. However, as presented in Fig. 8, the simulation configurations being extensive but not comprehensive, still fails to capture such behavior. Clearly, our analytical model is essential not only to confirm and complement the simulations, but also to supply inherent clues to how changes in network parameters translate into performance variations.

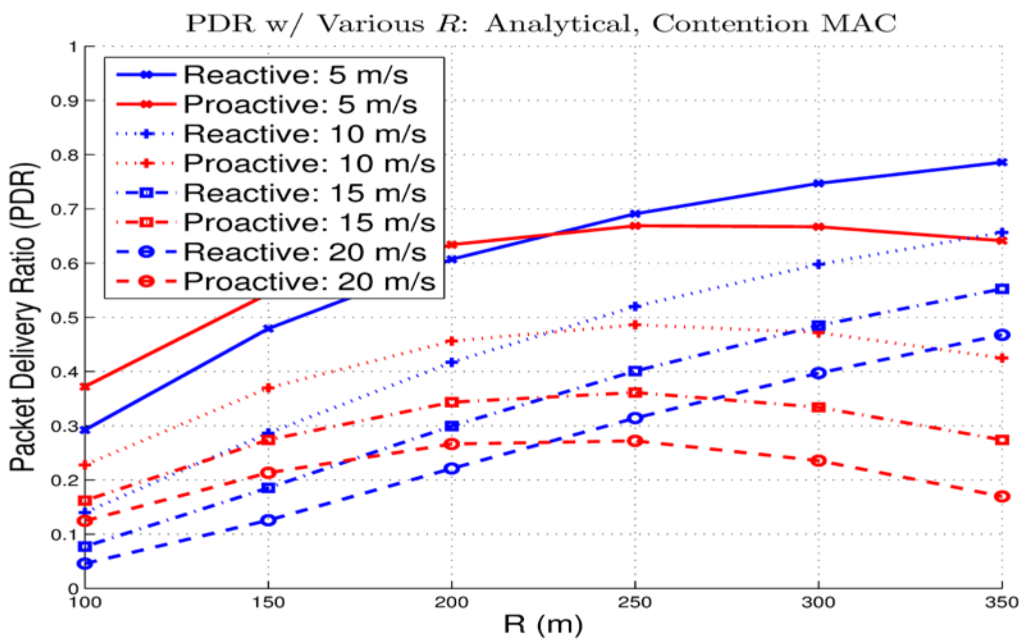

Fig. 7. Packet Delivery Ratio (PDR), Various R Analytical, Contention-based MAC.

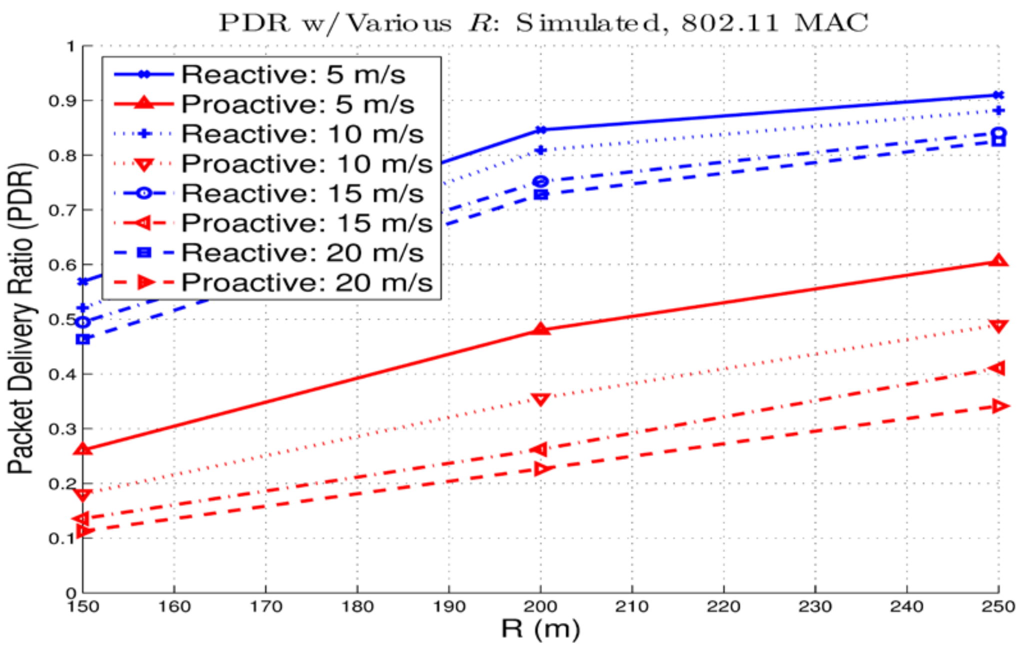

Fig. 8. Packet Delivery Ratio (PDR), Various R, Simulated, 802.11 MAC.

We also demonstrate how well the analytical model does in capturing the nodes mobility effect on the packet delivery ratio of both proactive and reactive routing protocols in Figs. 9 and 10. The larger the nodes movement speed is, the larger the probability of nodes moving out of transmission range is. Then the relay failure probability increases which causes the PDR decrease. Both analytical and simulation results agree with this intuition, i.e, the proposed model still captures the essential behaviors of routing protocols with respect to mobility. Especially, the model provides excellent match to simulated performance for proactive routing protocols. However, because reactive routing protocols request routing path information right before routing which greatly increases the unreliability in higher mobile scenarios, the model fails to provide good matches to simulated performance which is expected.

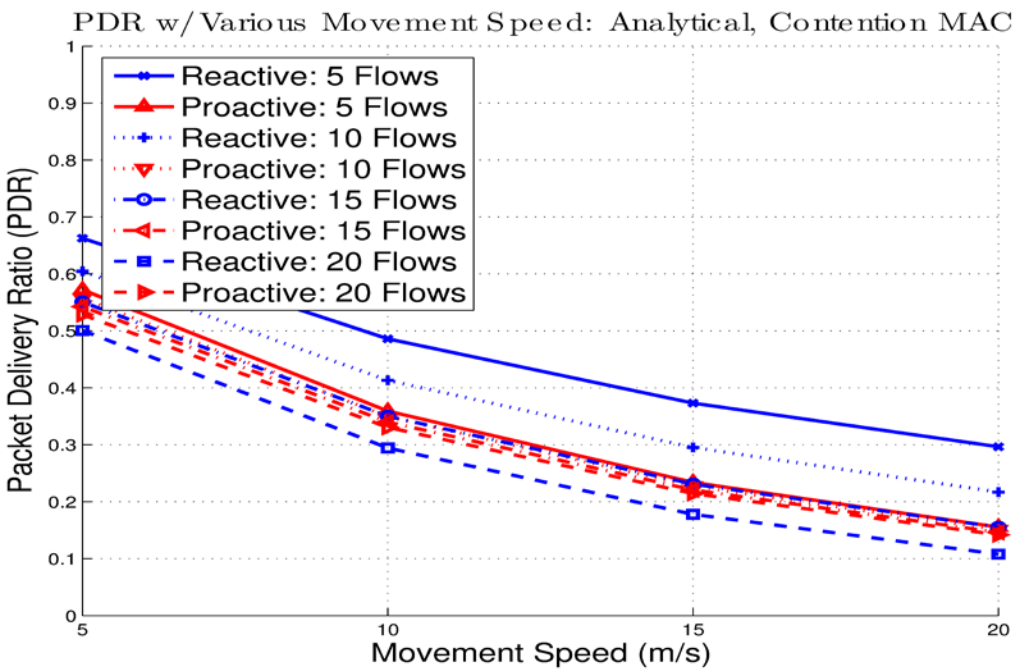

Fig. 9. Packet Delivery Ratio (PDR), Various V, Analytical, Contention-based MAC.

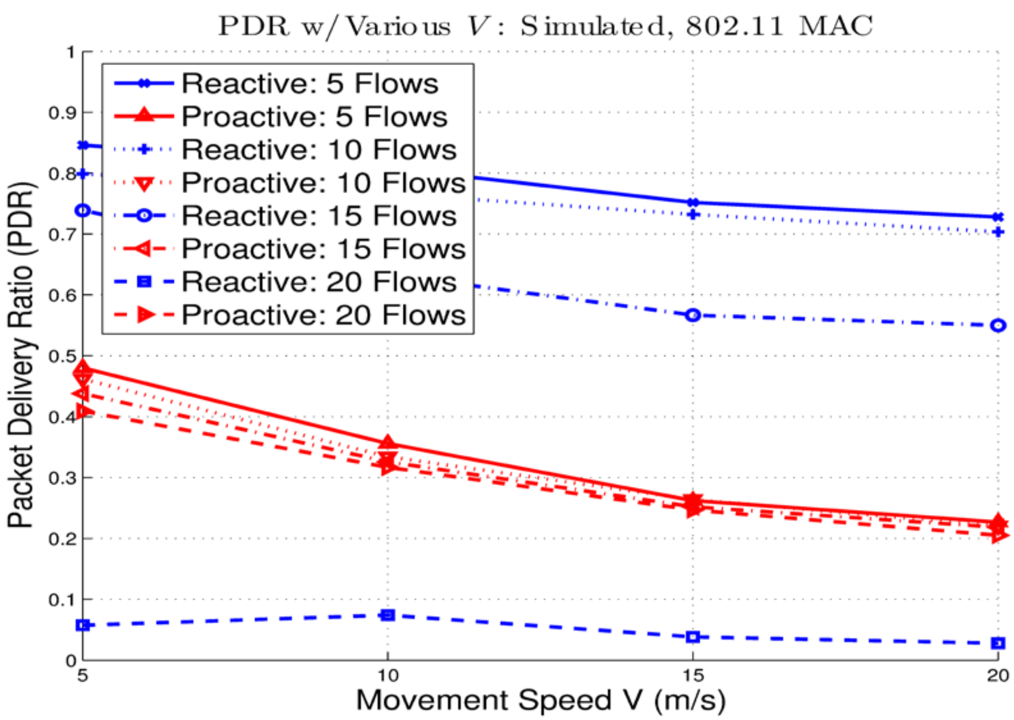

Fig. 10. Packet Delivery Ratio (PDR), Various V, Simulated, 802.11 MAC.

After looking into PDR, let's look at the packet delivery delay with various traffic flow F, transmission range R and movement speed V. From Figs. 11 and 12, the following observation is concluded.

• Theoretically (shown in Fig. 11), proactive routing protocols periodically update routing path information to guarantee packets sent out immediately, therefore even arrival packets number increases as traffic flow increases, they still can be sent out in time which causes the stability of packet delivery delay; however, in real networks, network capacity could still limit the packet processing speed (shown in Fig. 12). Heavy traffic constraints the routing request process of reactive protocols which increases the packet delivery delay; simulation results in Fig. 12 for reactive routing protocols validate the theoretical model.

In summary, the parametric analytical framework could also capture the essential insights and behavior of routing protocols in terms of packet delivery delay. Even with nodes mobility and traffic load factors, the model still can provide satisfactory approximation to simulated performance.

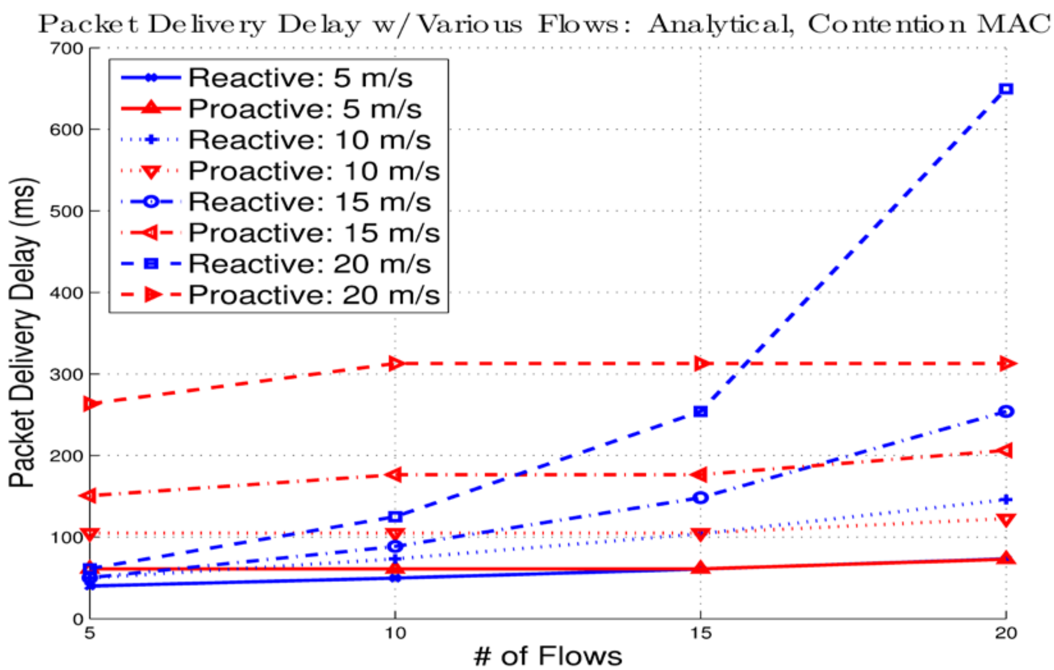

Fig. 11. Packet Delivery Delay, Various Flows, Analytical, Contention-based MAC.

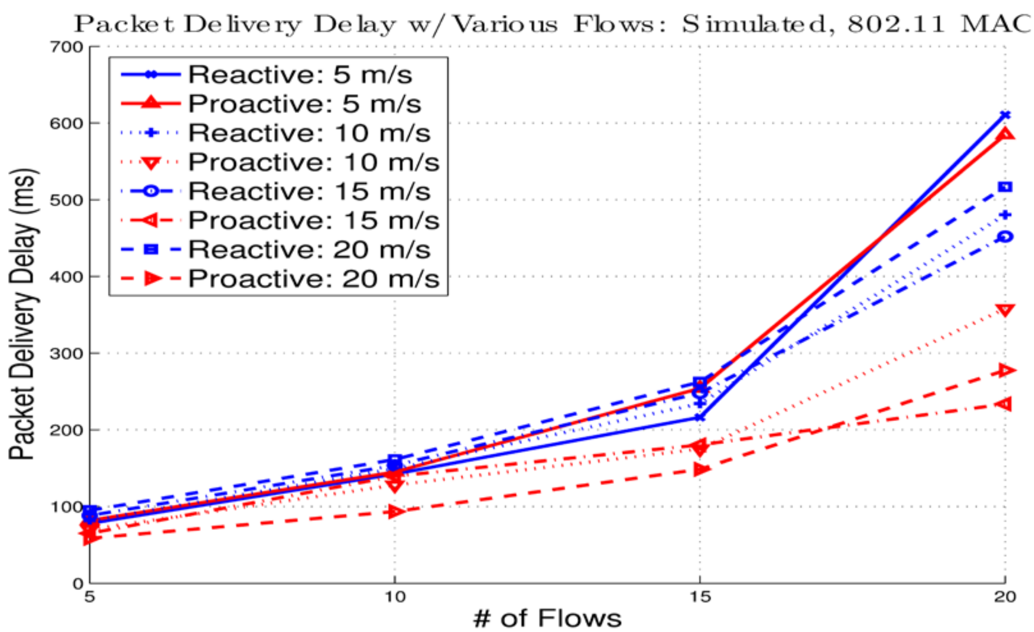

Fig. 12. Packet Delivery Delay, Various Flows, Simulated, 802.11 MAC.

3 Ph.D. and M.S. Theses Completed

During this program, more than 20 students received funding from this program and completed their theses. The names of these students were mentioned in prior annual reports and will not be repeated here again.

4 Honors and Awards

Numerous best paper awards and honors were received which were supported by this program. The complete list can be founded from previous reports and we simply mention a sample of them in this report.

- Best paper award at IEEE Fred W. Ellersick Award for Best Unclassified Paper at the 2008 Milcom conference.
- Best student paper award at IEEE European Wireless 2010 conference.
- Best paper award at IEEE 2008 International Conference on Communications (ICC).
- 2007 Gilbreth Lectureship from the National Academy of Engineering.
- 2008 AACC Richard E. Bellman Control Heritage Award.
- Honorary Doctorate at Technical University of Crete.
- Best paper award at 2008 IEEE International Conference on Mobile Ad-hoc and Sensor Systems.